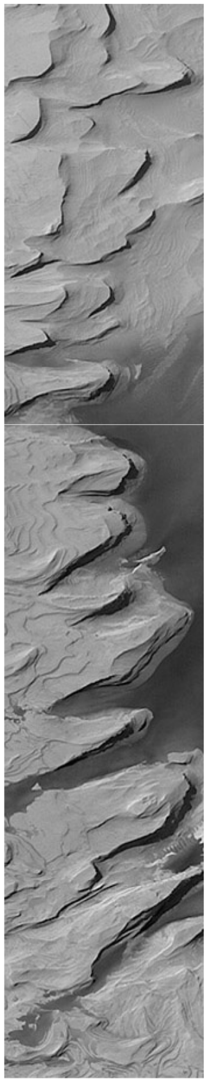


Novel Ultrasonic Horn Designs for Extraterrestrial Applications

Stewart Sherrit
Jet Propulsion Laboratory, Caltech

April 18,2012

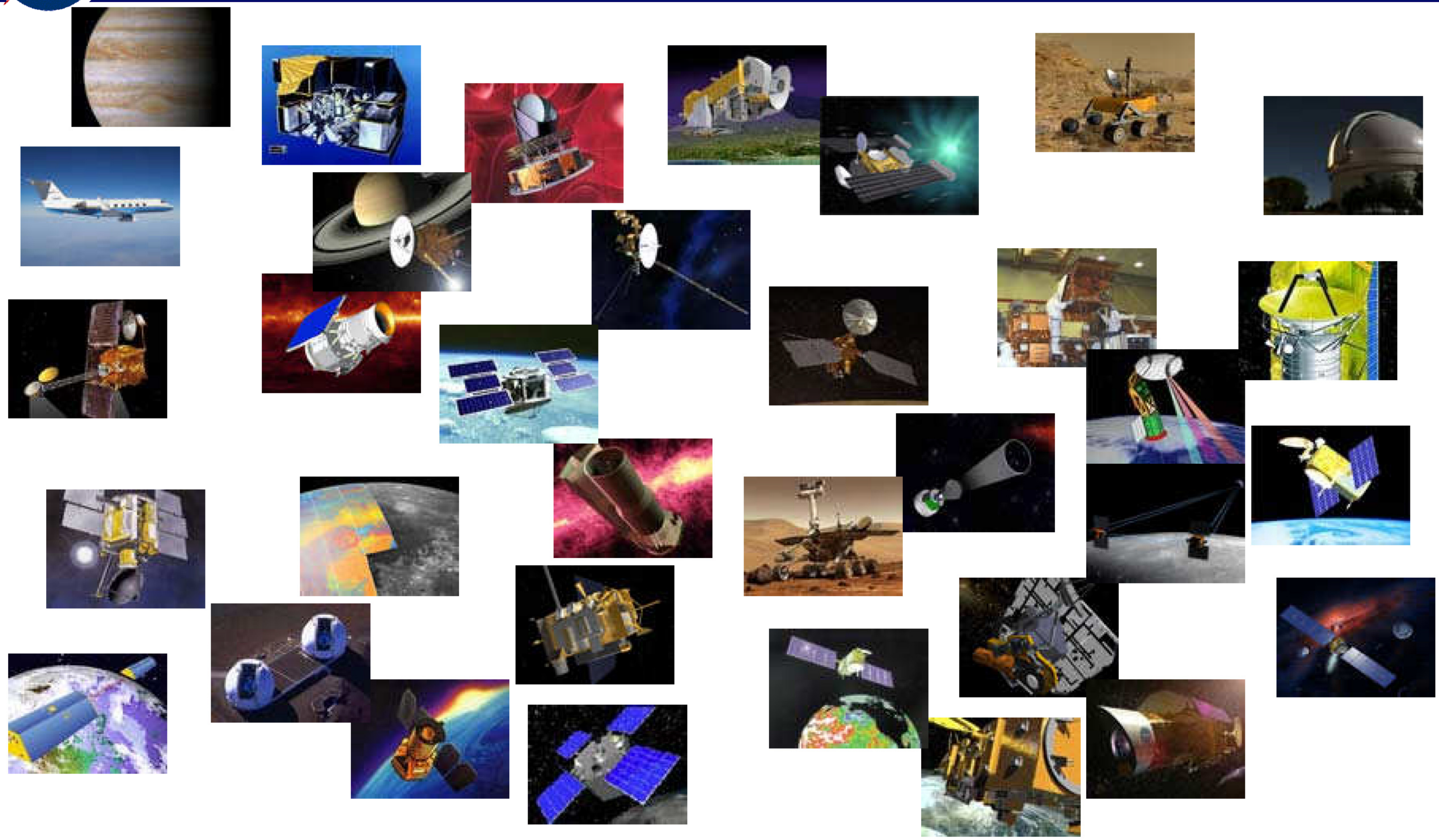
UIA Presentation – San Francisco – April 2012

© 2012 California Institute of Technology. Government sponsorship acknowledged.

Outline

- What does JPL do?
- Who are we?
- What we do!
- Chronology of Sampling technology development
  - Lithotripsy
  - Ultrasonic Sonic Driller Corer USDC
  - USDC –Ultrasonic Rock Abrasion Tool (URAT)
  - Inverted Stepped Horns
  - Folded Horns
  - Flipped horns
  - Dog Bone Horns
  - Flexure Monolithic Horns
  - Asymmetrically grooved horns

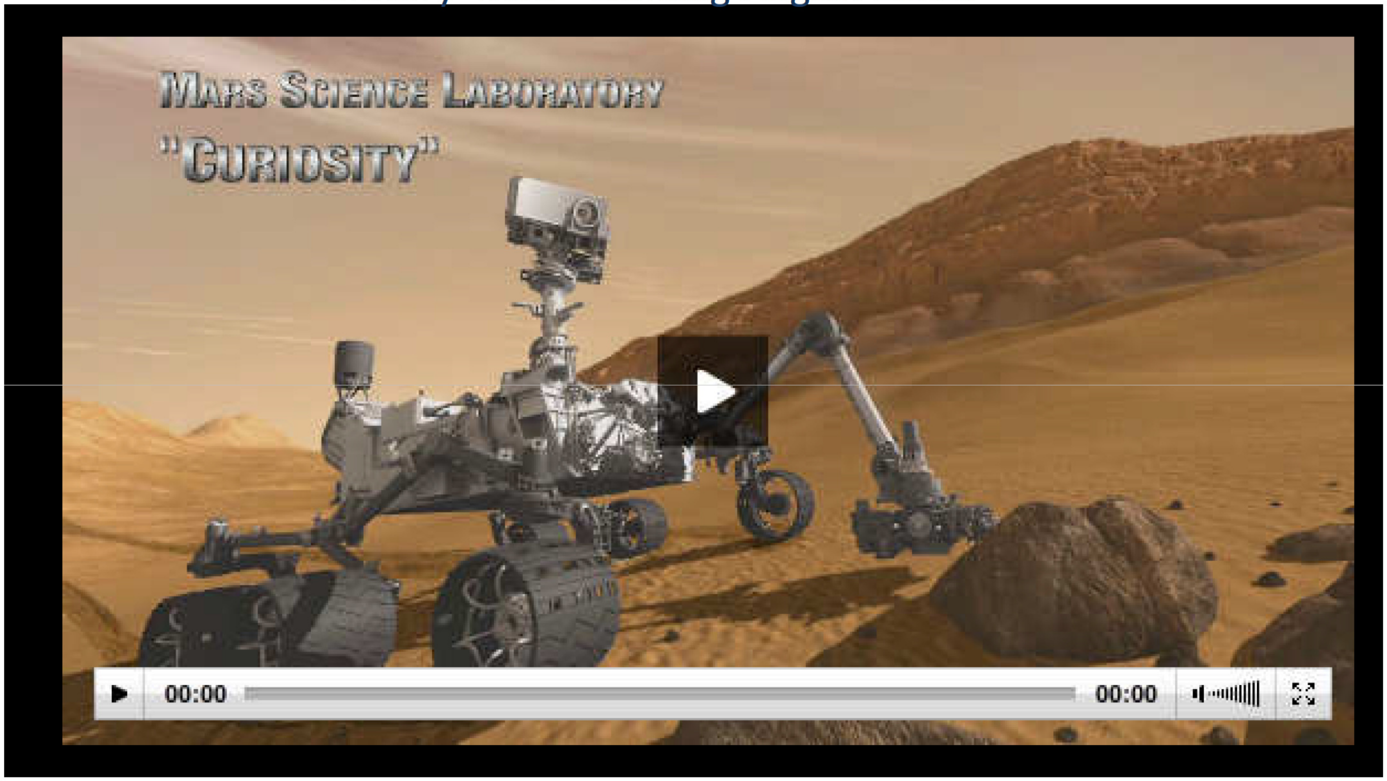
What do we do?
Currently over 30 missions with JPL instruments
Exploring the Solar System (March 2012)



See - http://www.jpl.nasa.gov/missions/index.cfm?type=current

Example of a current Mission at JPL!

Mars Science Laboratory MSL – Landing August 2012!



http://mars.jpl.nasa.gov/msl/multimedia/videos/index.cfm?v=24

Advanced Technologies Group/ NDEAA Lab - Who Are We?

Compilation of Physicists and Mechanical Engineers with backgrounds in Ultrasonics, Mechanisms, Piezoelectrics, NDE, Dynamics

http://ndeaa.jpl.nasa.gov

What we do: Our Niche

Sampling

- ❑Drills
- ❑Corers
- ❑Rock Abrasion Tools
- ❑Powder Samplers

Sample Handling

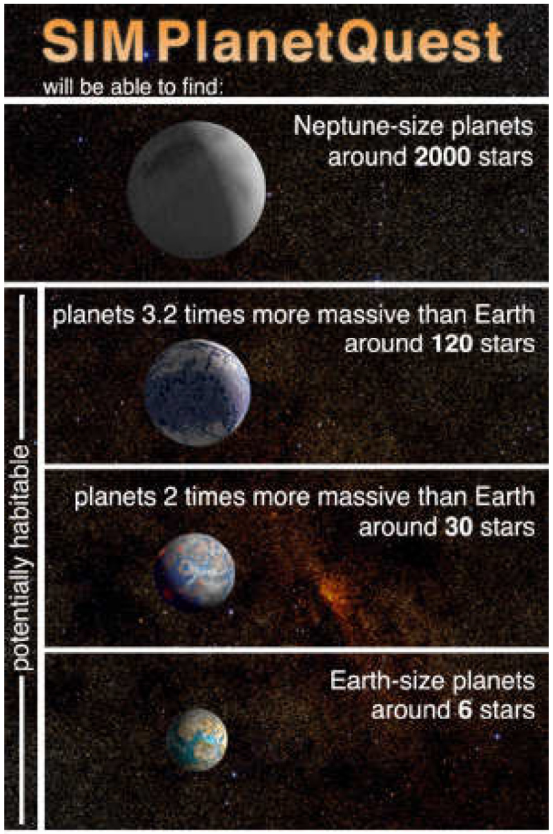
- ❑Powder Vibrators
- ❑Vibrating Funnels
- ❑Vibrating Sample Holders

Micro-positioners

- ❑Active mirrors
- ❑Linear Actuators
- ❑Rotary Actuators

Usually use piezoelectric materials
Although we are open to other ways of doing it!!!

Micro-positioners eg. Space Interferometry Mission



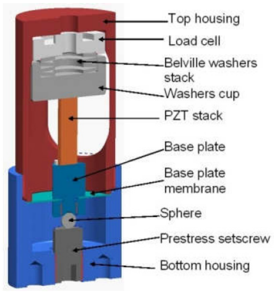
- 3 interferometers
- 2x7.2 and 9 m baselines
- Earth trailing solar orbit
- 5.5 year mission life with goal of 10 years
- Over 200 piezoelectric stacks

- MISSION CANCELLED - 2011

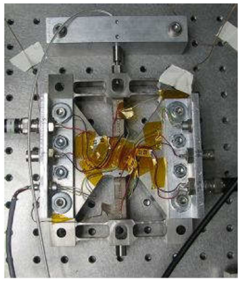
Micro-positioners – SIM – Our role

Develop a series of life tests to insure full mission life

- AC lifetest#1 60 Vpp, 2kHz, 10^{10} cycles



- AC lifetest#2 20 Vpp, 2kHz, 10^{11} cycles



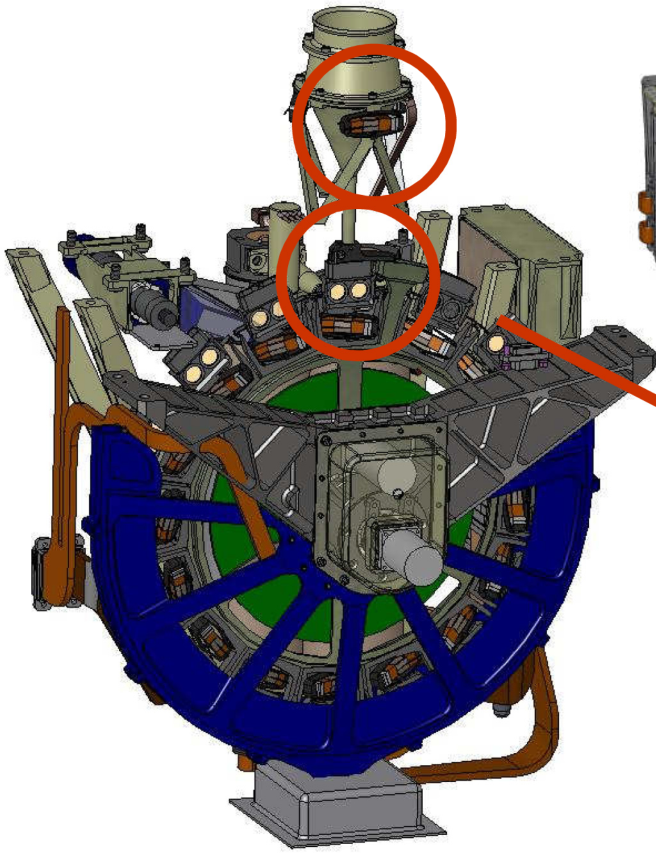
- DC life test - 100 Volts DC- Controlled Humidity

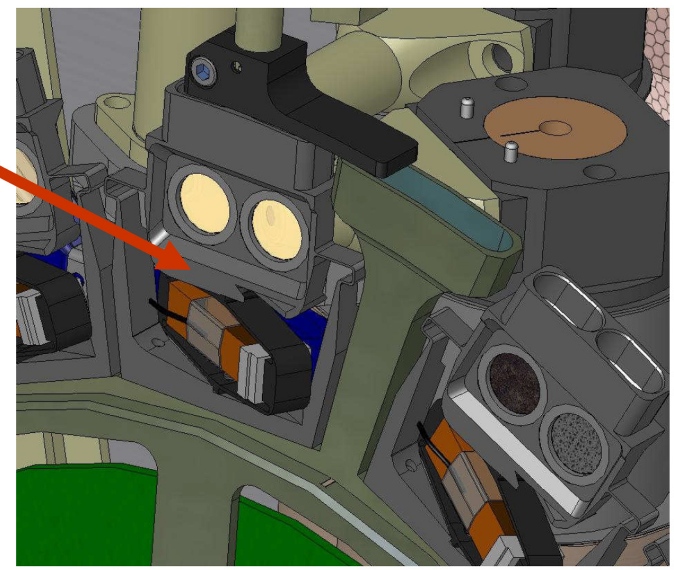
Incomplete due to mission cancellation

- See Sherrit et al. 2008, 2011

MSL Instrument - CHEMIN – XRD XRF – Sample cell shaker and inlet funnel

Original Design- problems at Mars ambient and under launch random vibe.

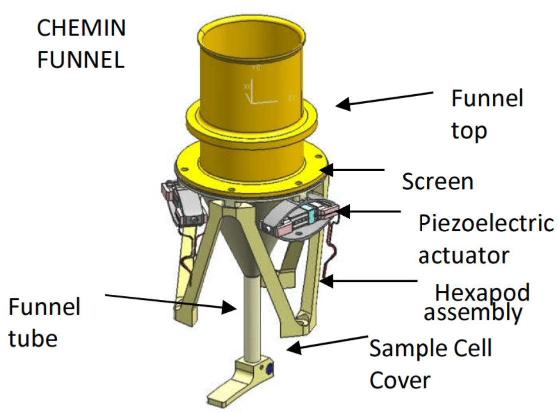


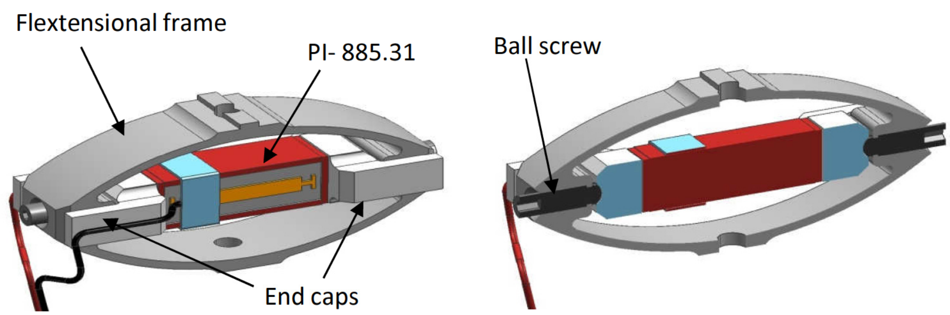


Sample Handling – Our Role

MSL has 21 piezoelectric actuators for sample handling and instrument cells

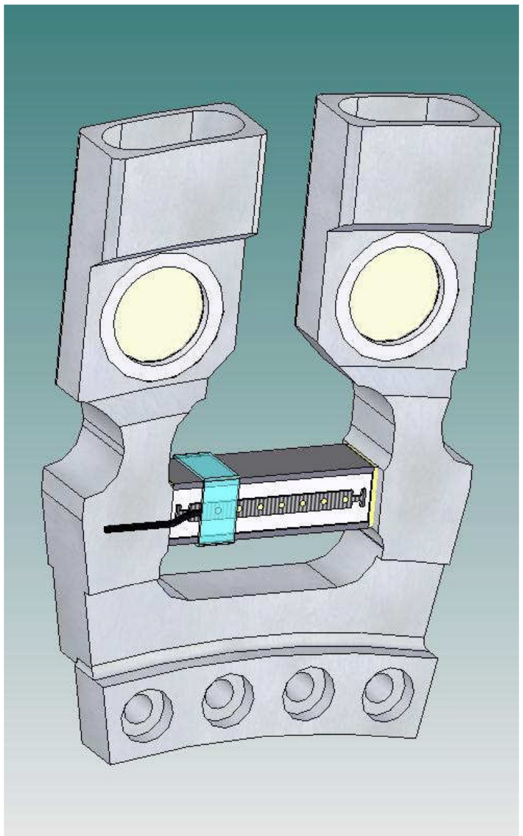
- 2 on SAM inlet funnel
- 3 on CHEMIN inlet funnel for powder delivery assist
- 16 on CHEMIN instrument sample wheel





See Sherrit et al. 2009

Sample Handling – Our Role



MSL Sample cell Shakers Re-design

Phillippe Sarrazin (Inxitu) came up with tuning fork design and with Eric Olds (Swales) they came up with

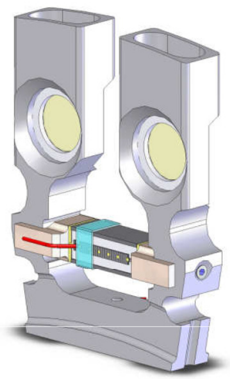
Problems

1/ Thermal analysis showed marginal thermal stress on piezoelectric

2/ Wheel mounting created anisotropic stress. (Energy to wheel)

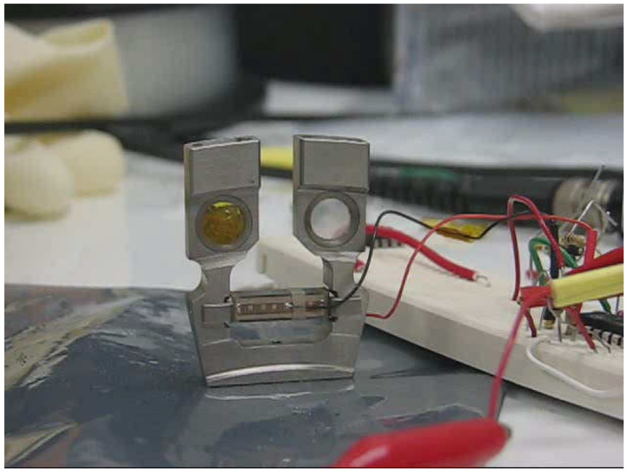
Sample Handling – Our Role

MSL Sample cell Shakers Re-design fine tuning -



Solutions

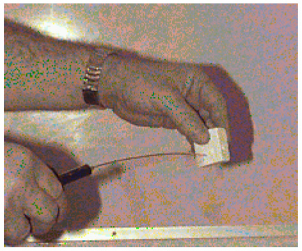
1/ Shorten Piezoelectric
2/ Use Invar end caps
3/ Use ball/set screw mount
4/ Soften Tuning fork
5/ make base symmetric

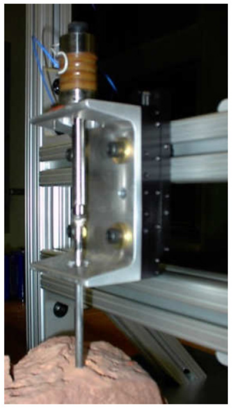


See http://msl-scicorner.jpl.nasa.gov/Instruments/CheMin/

Sampling

Started out looking at pure ultrasonics with Cybersonics Inc. (Erie, PA)
Discussions with Cybersonics Inc. led to the development of the USDC





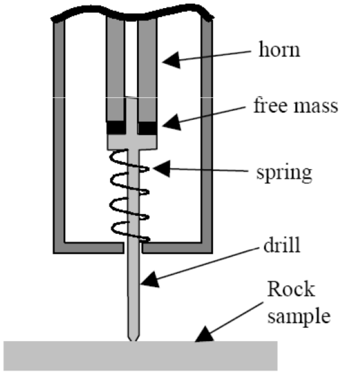
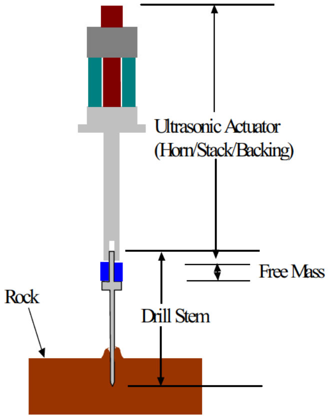


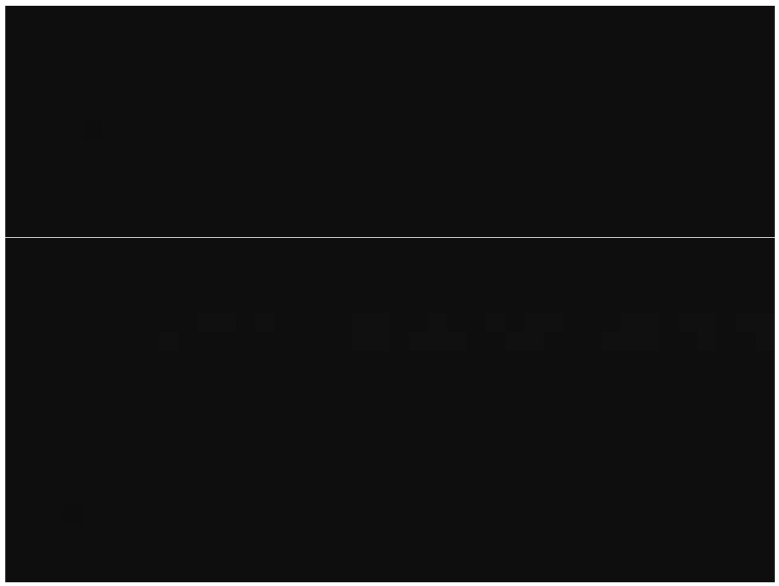
Figure 8. Schematic cross section of the drill assembly with restoring spring and impedance matching mass.



First paper describing the technology - see Sherrit et al. (1999)

Sampling

Initial development was mainly experimental- looking at ways to improve or expand the technology.

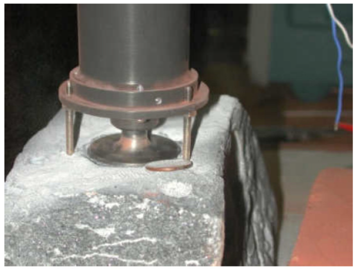


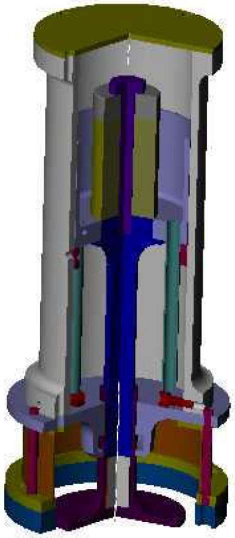
http://www.youtube.com/watch?v=phLiWya1sGo

First real engineering occurred when USDC was selected (URAT) for backup Rock Abrasion Tool on the Mars Exploration Rovers (MER)

Sampling

(URAT) Ultrasonic Rock Abrasion Tool -Mechanical design and fabrication along with flight like electronics (FPGA switching H-bridge)





The initial response was, “This is great. Can you make it Shorter?”
Which is how we started to develop novel Ultrasonic horns

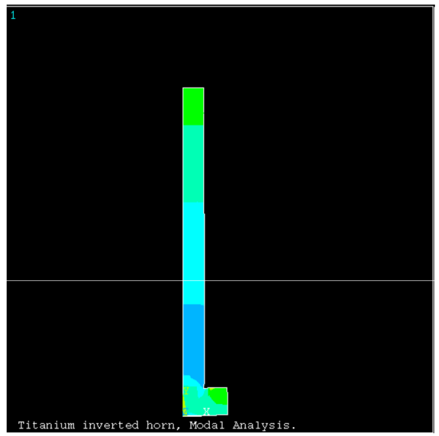
Sampling – Folded Horns

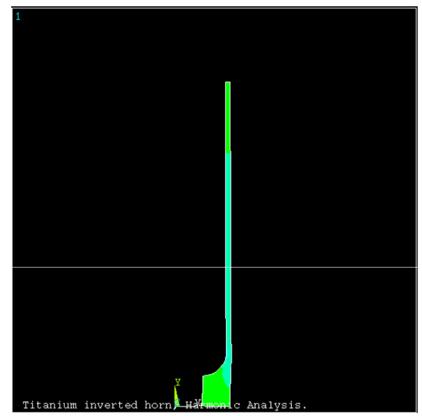
Q: How do you create at 20 kHz ultrasonic horn and make it short?

A1: Fold it

Axisymmetric Models

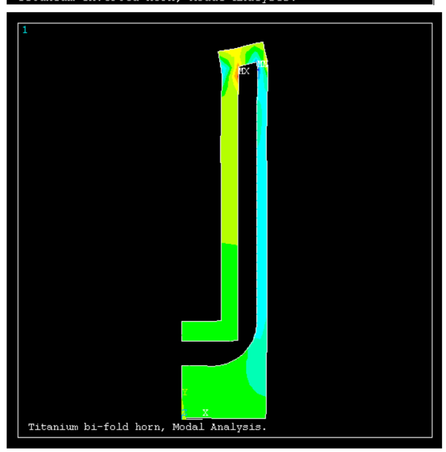
Stepped

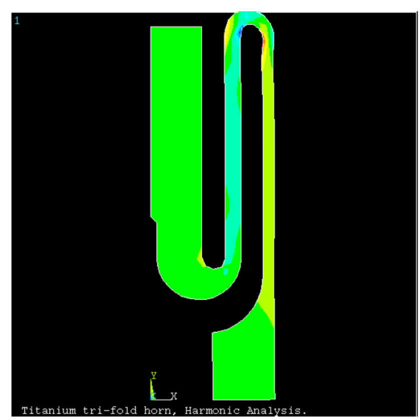




Inverted Stepped

1 fold

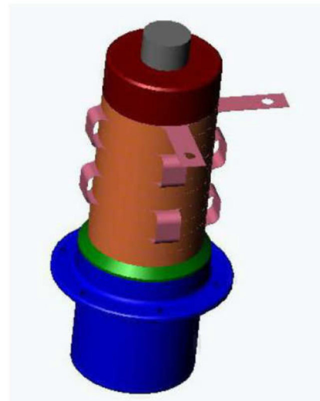


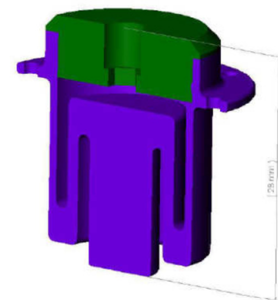


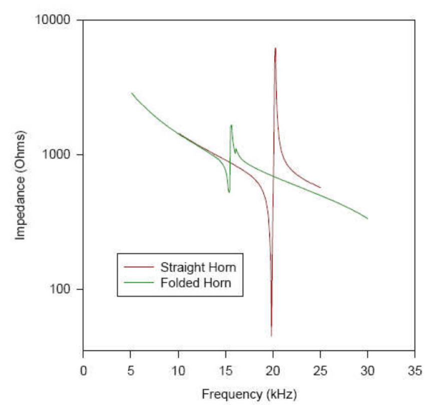
2 fold

Sampling – Folded Horns

Design and tested the doubly Folded horn-

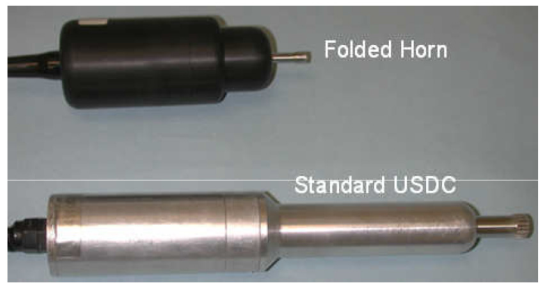




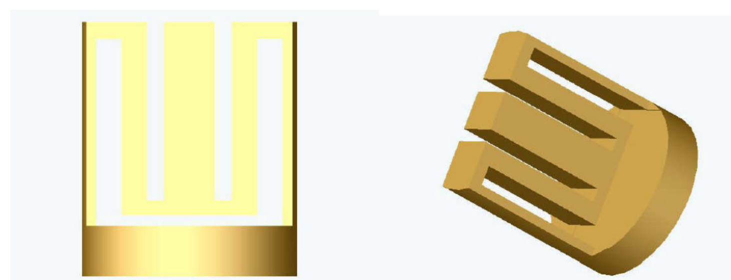


Sampling – Folded Horns

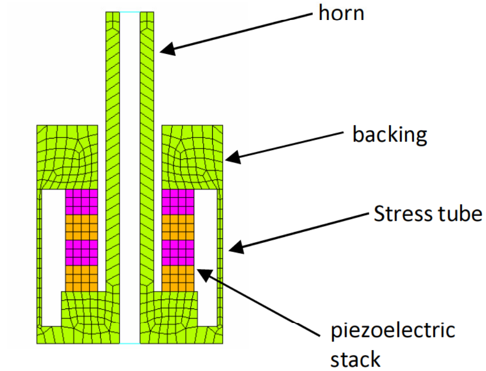
Incorporated the horn in a non-pneumatic rock powder sampler

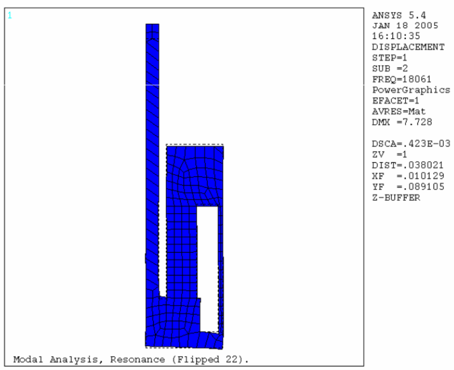


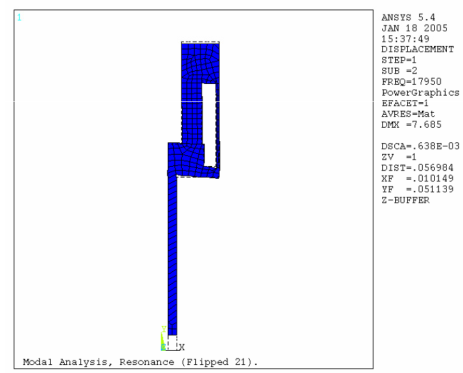
We also came up with a solid planar
Monolithic version. See Sherrit et al. 2002



Sampling – Flipped Horns







	Flipped horn	Standard horn	Difference (%)
Resonance frequency (Hz)	18061	17950	0.61
Horn-tip disp. (m), 1 volt	4.62×10^{-7}	4.63×10^{-7}	0.22
Electric current (amp), 1 volt	1.05×10^{-2}	1.04×10^{-2}	0.95
Max. stress (Pa), 1 volt	2.50×10^{6}	2.24×10^{6}	10.4
Horn-tip disp. (m), 1 watt	4.51×10^{-6}	4.54×10^{-6}	0.67

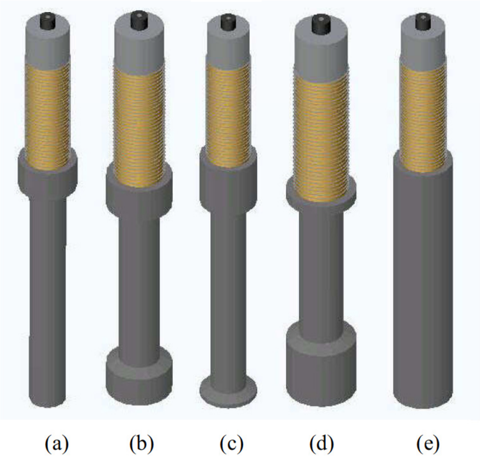
Table 1. Comparison of performance of the flipped and the standard horns.
See Chang et al. 2005

Sampling – Dog-bone Horns

For an impact device the interaction time is of the order of 50 μs
Which suggest at the tip for maximum momentum transfer the tip
Thickness should be less than ≈ 50 μs *4000 m/s = 0.02 m

The 5 designs of ultrasonic horn studied:

a) Conventional
b) Neck at middle span of horn
c) Neck moved down 20 mm
d) Neck moved up 20 mm
e) No neck



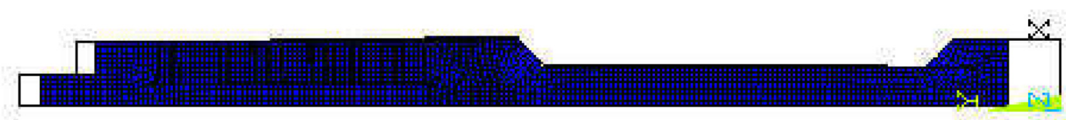
Horn Type	Horn length (mm)	Resonance (Hz)	Anti-Resonance (Hz)	Coupling Factor	Max. Displacement (mm)
Conventional	250	5314	5726	0.372	0.209
Neck at middle	200	5473	5947	0.391	0.185
Neck up 20 mm	175	5421	5916	0.400	0.185
Neck down 20 mm	255	5266	5666	0.369	0.209
No Neck	240	5304	6016	0.472	0.133

See Chang et al. 2004

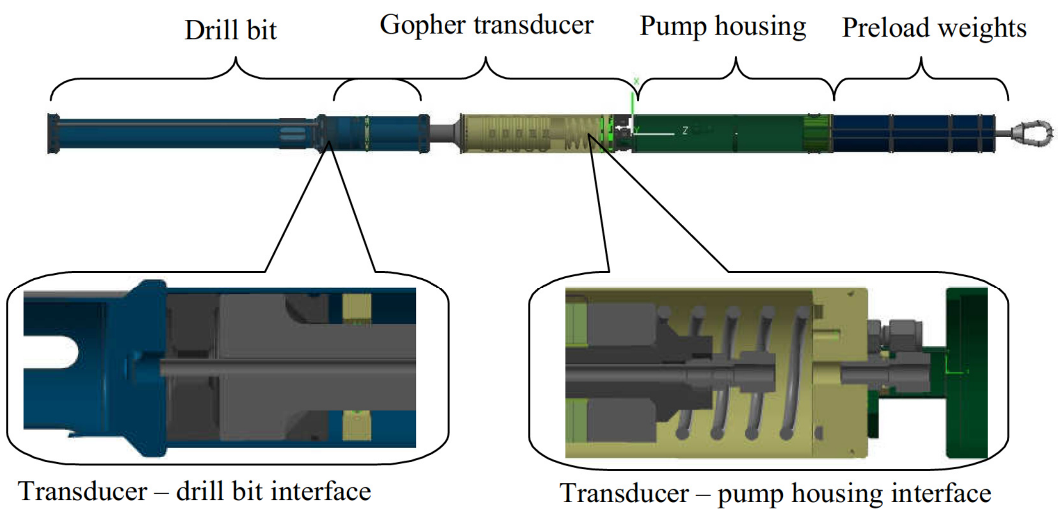
Sampling – Dog-bone Horns
Analytical Modeling

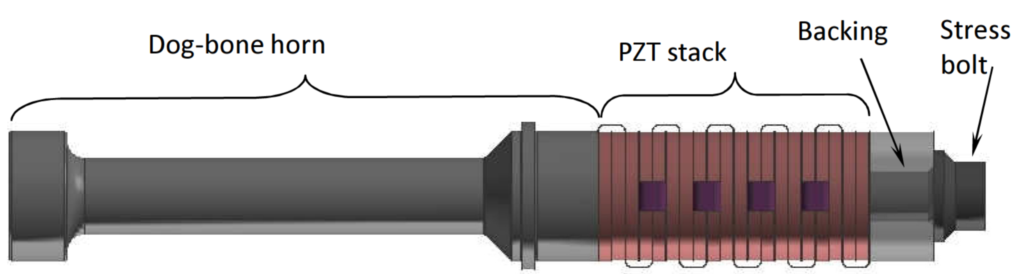
Integrated program package:
Modal analysis – Resonance
Modal analysis – Anti-resonance
Harmonic analysis
Simplified integrated model
Impact analysis
Spring-mass model

Resonance frequency 5195Hz



Sampling – Used Dog-bone Horn to produce Ice gopher Wire-line hammer drill

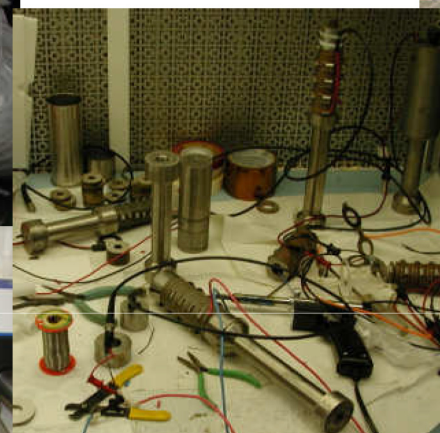


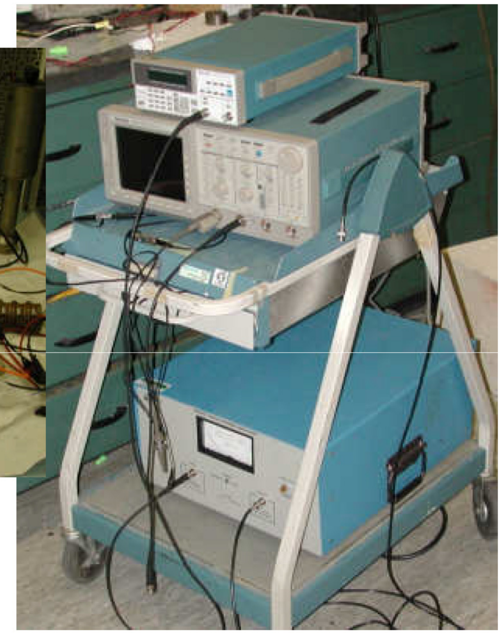


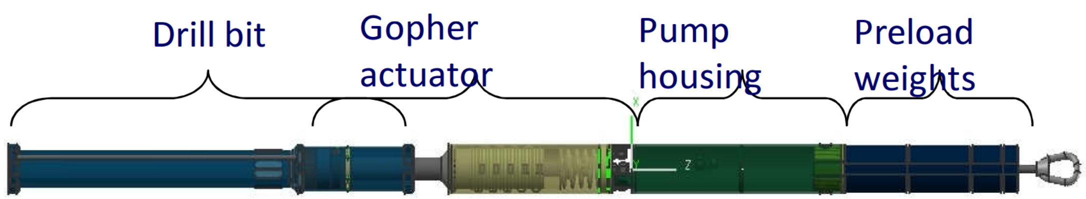
Components

- Gopher Actuator(Transducer)
- Drill bit
- Free mass
- Pump
- Preload

Gopher Design Fabrication

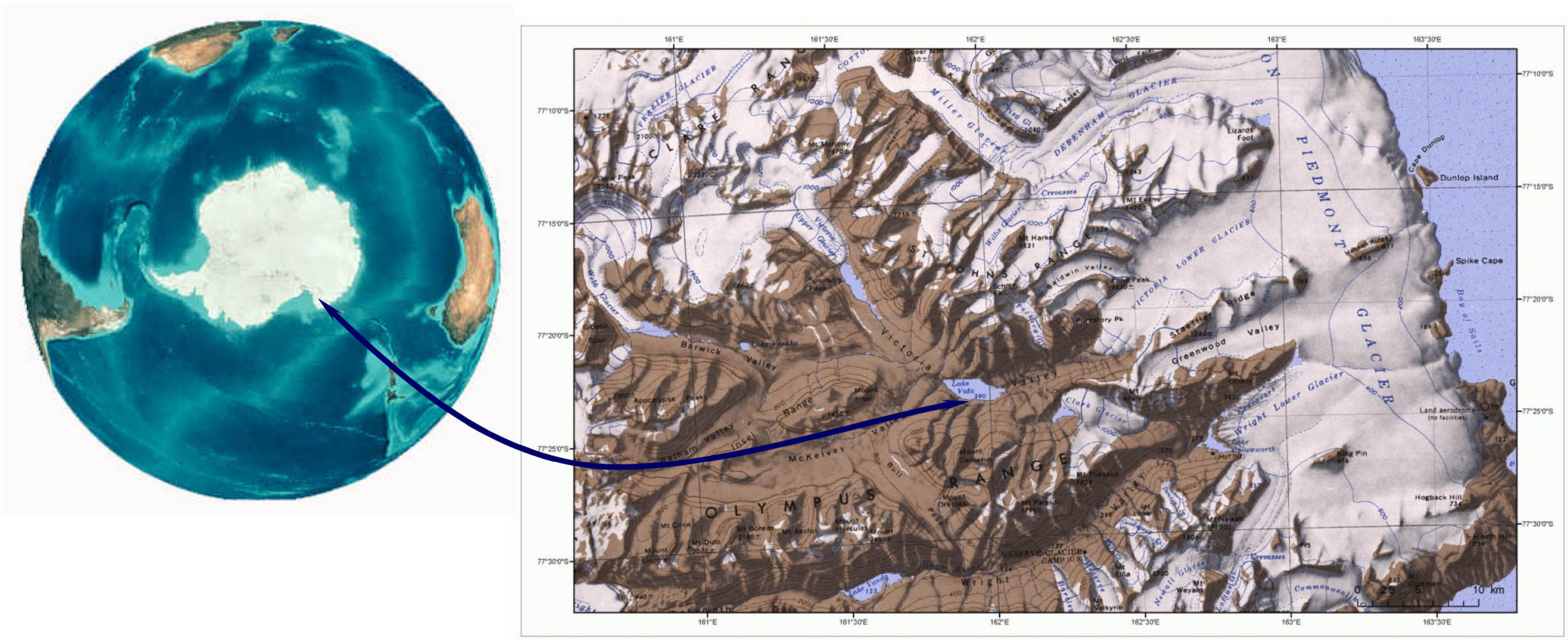






Gopher Field Trips – Mt. Hood, Oregon

Gopher Field Trips – Lake Vida, Antarctica



Lake Vida (77.23ºS 162ºE) in the McMurdo Dry valleys, Antarctica, offers a Mars analog environment for testing the detection and description of life in a previously unstudied extreme ecosystem

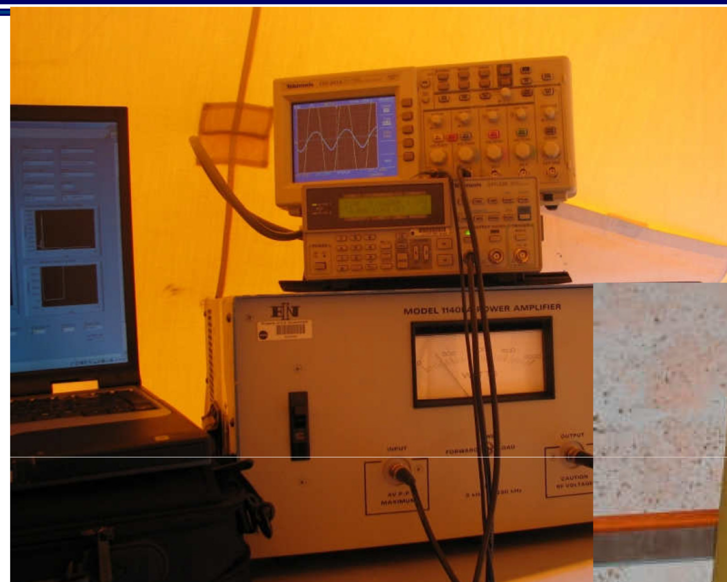
Gopher Field Trips – First McMurdo, Antarctica

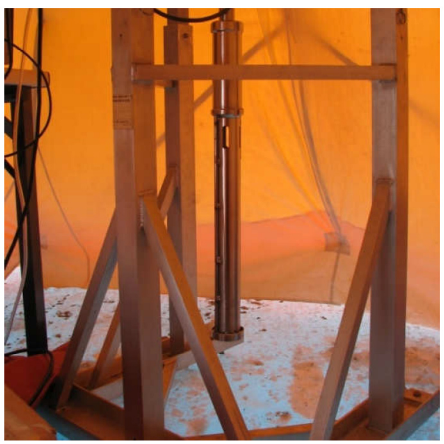
Gopher Field Trips – Lake Vida, Antarctica

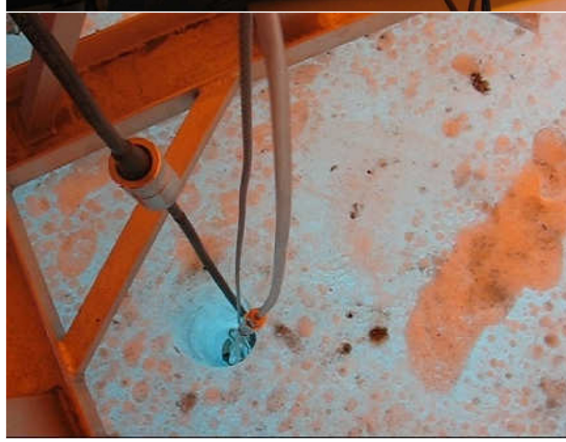
Gopher Field Trips – Lake Vida, Antarctica

Gopher Field Trips – Lake Vida, Antarctica

Gopher Field Trips – Lake Vida, Antarctica

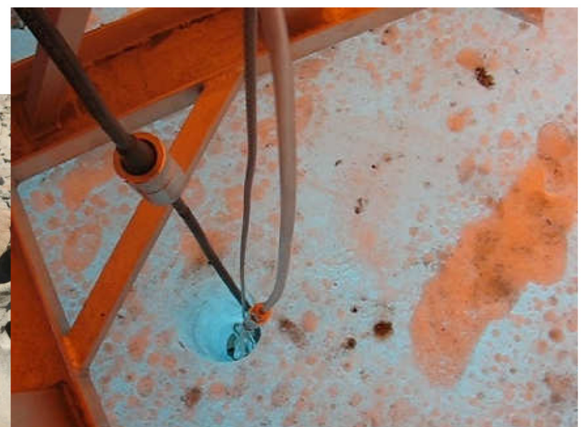






Gopher Field Trips – Lake Vida, Antarctica
Results

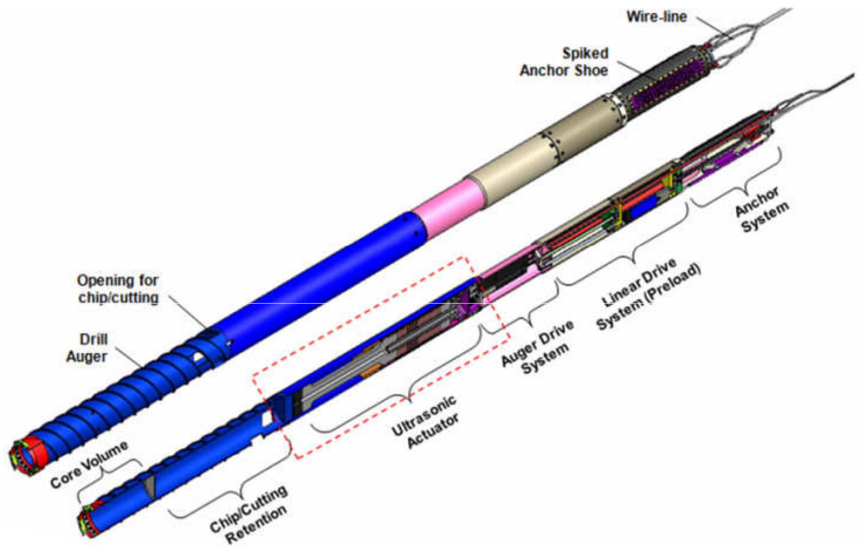
- Demonstrated that the technology is feasible
- Learn about challenges and design changes required to enhance its drilling capability
- Drilling depth of 1.76m is more than the total length of the Gopher including its support elements (pump, preload weights, etc.)



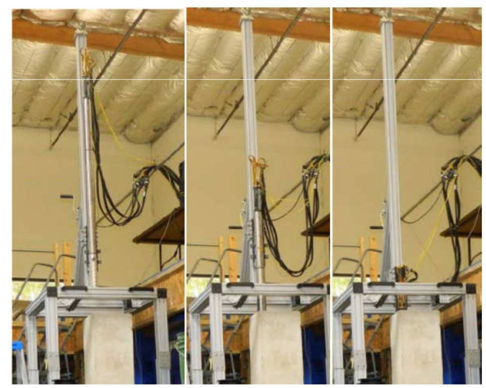
Ventifacts

Current version is Auto gopher

Rotary Hammer with sidewall anchors for deeper drilling



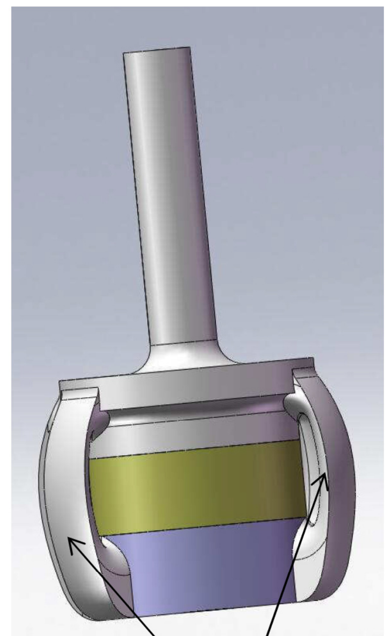
Demonstrated 2 m in limestone



See Bar-Cohen et al. 2012

Flexured horns: What are we doing?

Stress bolt

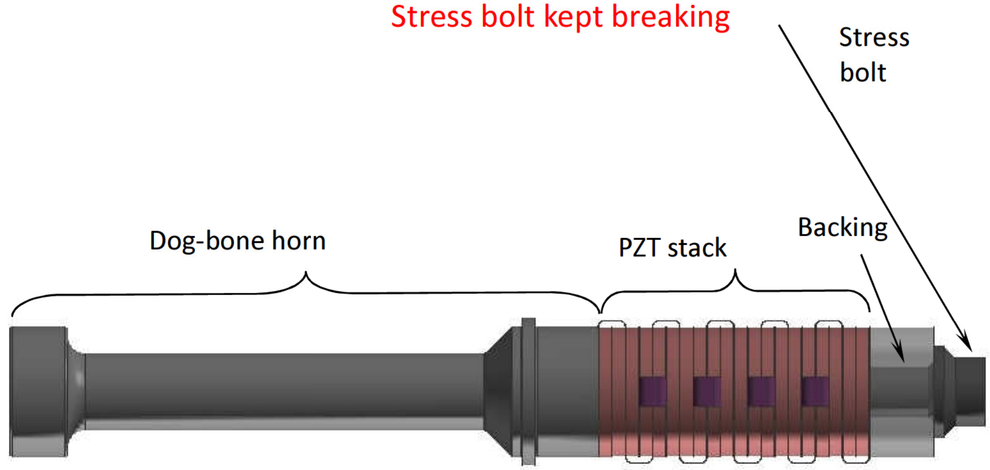


Pre-stress flexures

Flexured horns: Why?

When designing Gopher Actuator-Transducer

Stress bolt kept breaking



What other benefits of Pre-stress flexure

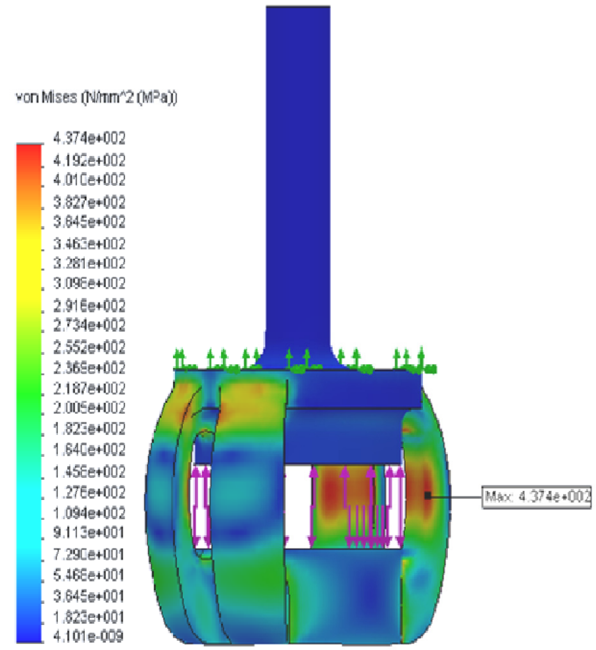
1. Increase manufacturing yield of disks vs rings
2. No Internal Discharge to stress bolt
3. Higher energy density
4. Pre-stress is not limited by bolt diameter
5. Actuator has higher coupling since it is not working against stiff bolt
6. Softer spring increases thermal preload stability

High Temperature Drill 500 °C

Bellville Washers

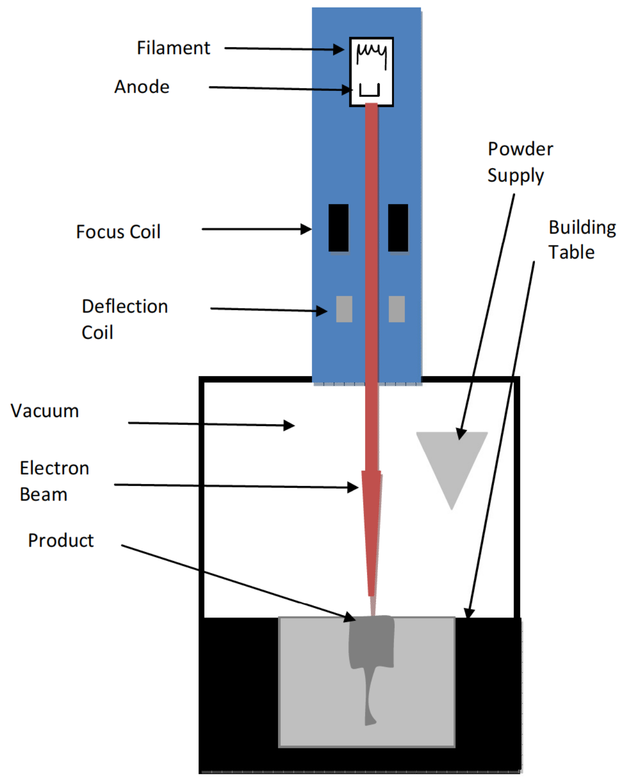
Design Example

Monolithic design



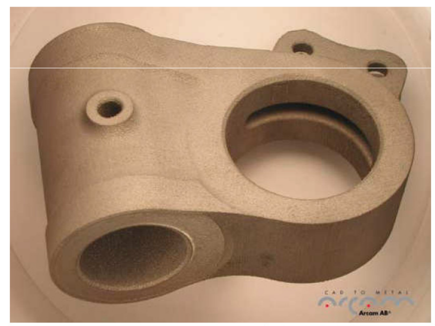
Manufacturing method - EBM

Chose EBM – Electron Beam Melting CALRAM Inc.



Examples from Arcam AB
- Landing gear component
- Tri-flange Implant

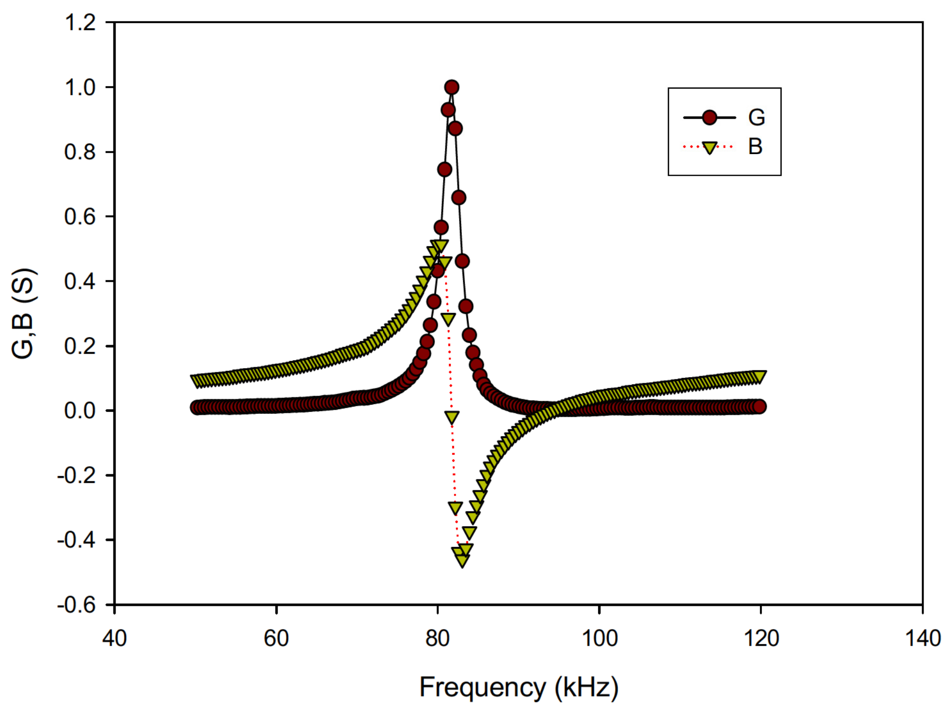
www.arcam.com



The design is also amenable to investment casting and other low cost high production techniques.

Can Use Solid Stacks

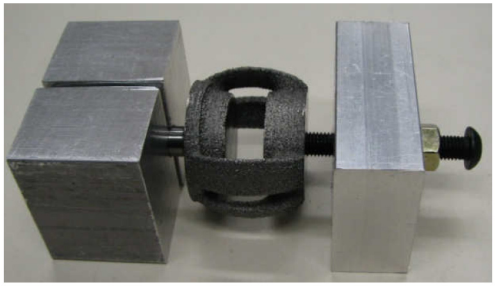
Impedance spectra of the bare Piezomechanik Gmbh bipolar stack (9.33 mm, 25.4 OD)



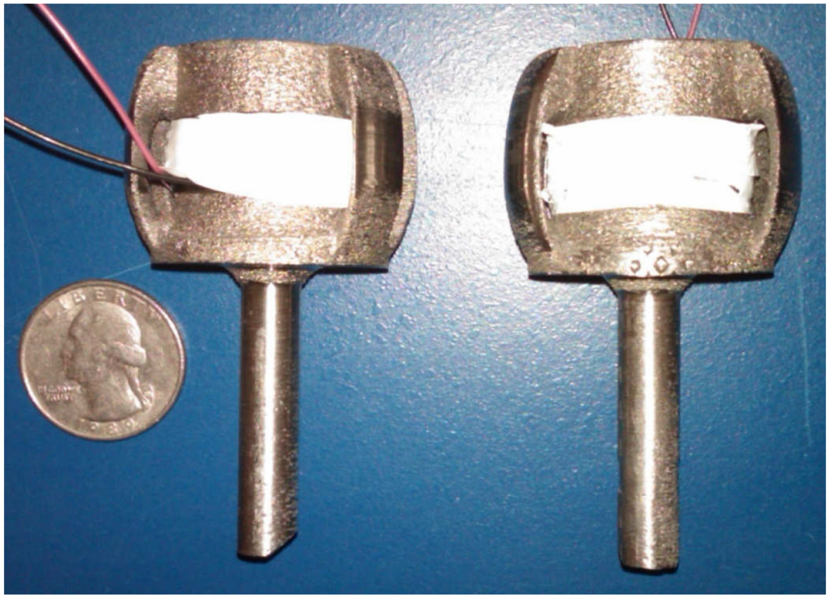
Small signal resonance analysis the bare stack

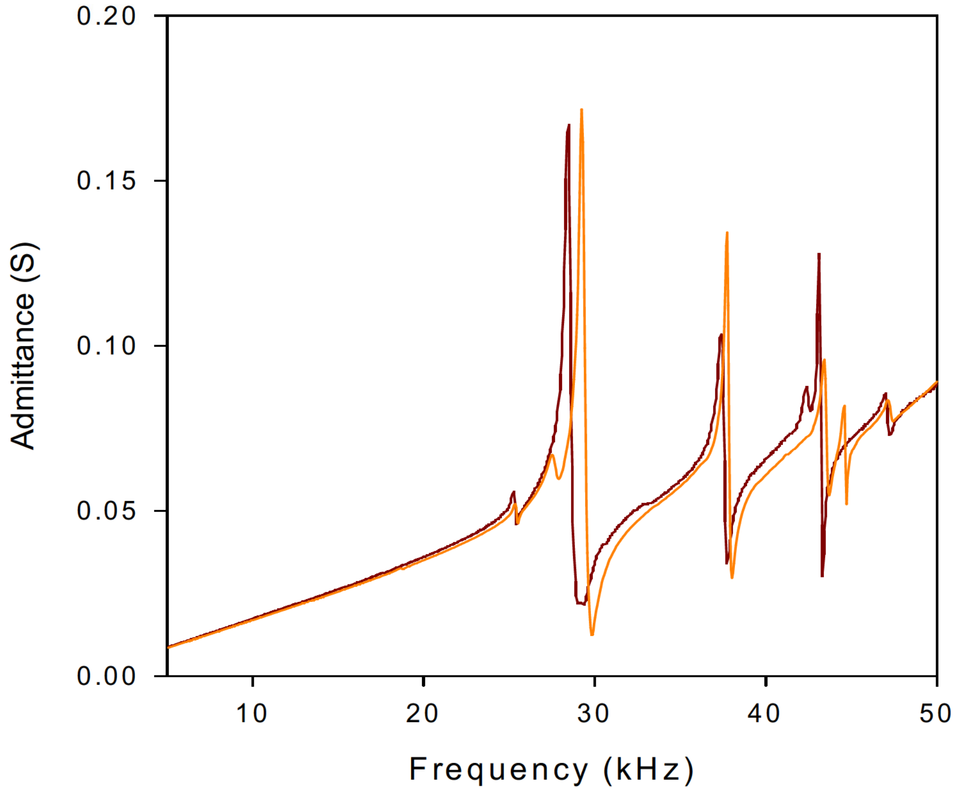
Material d33eff = 480 pC/N
Capacitance C=261 nF.
Coupling k_{33} =0.56
sE33=5.4×10^{-11} m^2/N
Q was 30.

Assembly



- Inner surfaces were finished using mill
- Flexures opened using pre-stress rig
- Stacks fixed using 3M 2216
- Preload monitored by measuring charge produced when flexures released





Assembled horns

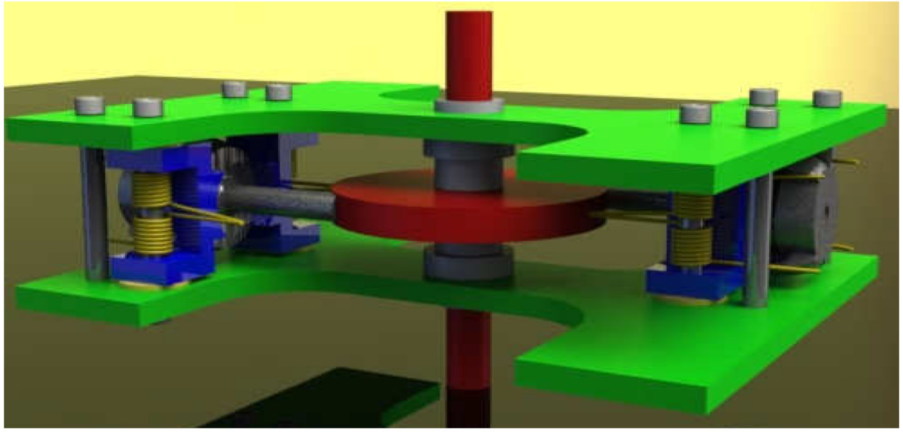
f_s =28.5-29.3 kHz

k=0.20-0.21

Mechanical Q's =106 , 115

Example application

Horns used in Barth Motor



Initial results - 15 RPM at 0.3 N-m

Movie of horn used as motor

Can we use horns to rotate and hammer?

Develop technologies for sample acquisition in extreme environments with reduced power, weight on bit and increased efficiency

- Hammering is great for breaking rock.
- Rotation is great for removing cuttings.
- This is why you have rotary hammer drills at Home depot

Can we develop a piezoelectric mechanism for hammering and with the same piezoelectric actuator induce rotation?

YES

Single Piezo-Actuator Rotary-Hammering (SPaRH) Drill

Drilling using Hammering is limited to a few centimeters depth without a debris extraction method. Rotation with augers is beneficial in that it aids drilling and extracts drilling debris.

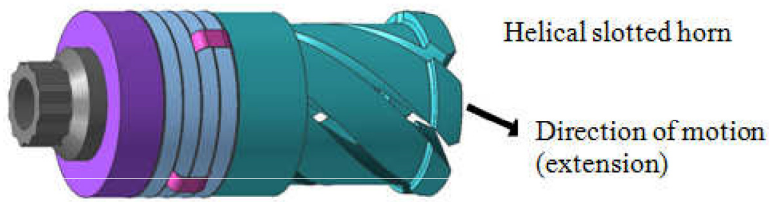
Previous approaches to induce rotation from extensional motion

- Create a bit with some asymmetry in shaft to induce rotation
- Impact wrenches/drivers
- Asymmetric teeth on bit

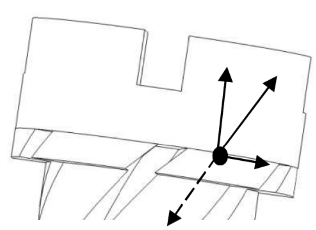
Approach

Use existing ultrasonic actuators / horns to create directional impacts on bit.

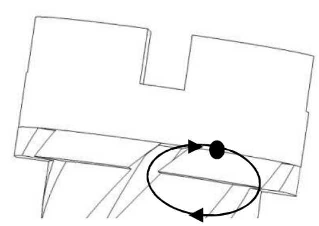
Use the micro-impacts of extension or bending at high frequency to produce macroscopic rotation.



extension



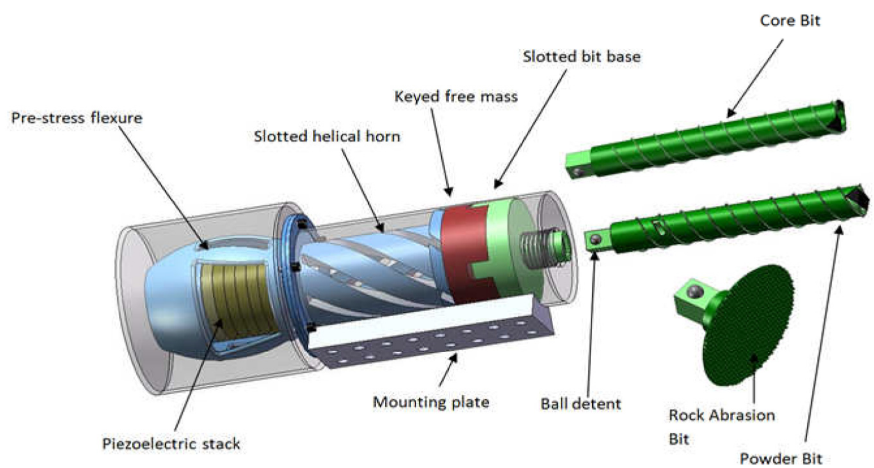
bending



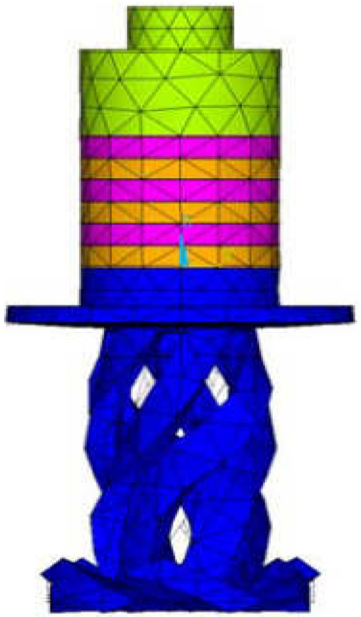
An Example Design and Analysis

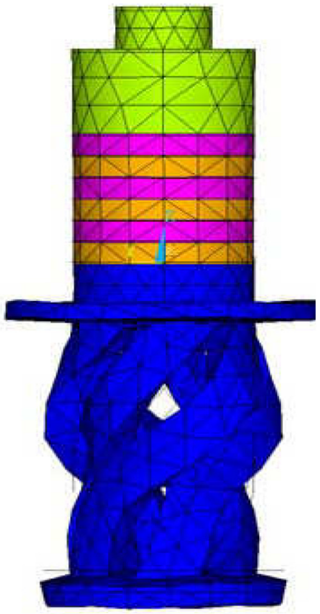
Design solution

Combine fluted bit rotation (cuttings removal) with Ultrasonic/Sonic percussion (drilled media fracturing and cuttings fluidization)



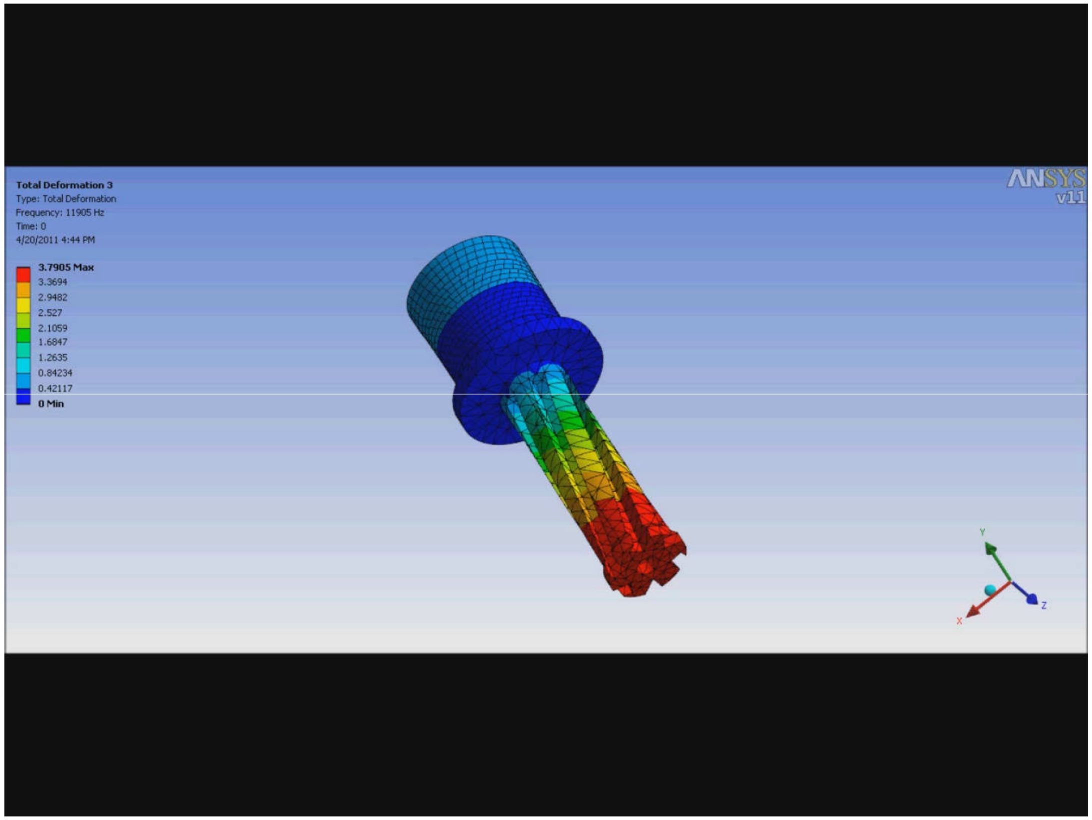
Horn Analysis





Looked at a large number of horn to produce twist and extension
Two rejected horn geometries are shown above.

An acceptable horn motion



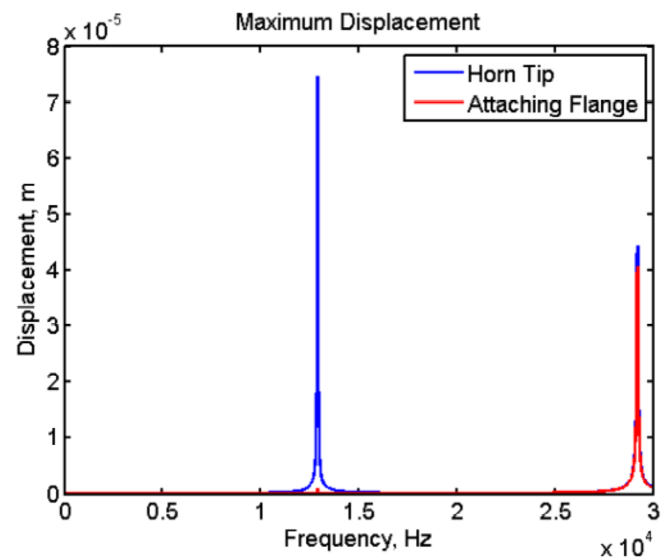
Horn Analysis

Harmonic analysis results suggest mode is reasonably coupled

Table 1. ANSYS predicted performance of chosen transducer design at 1 W input power.

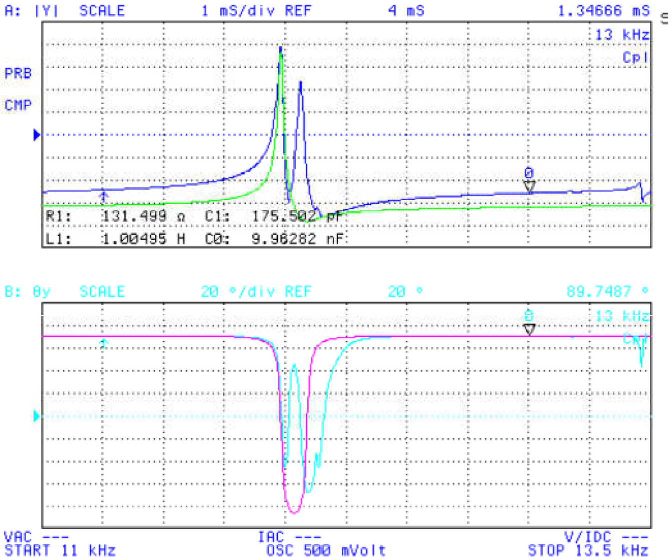
Frequency (First axial mode)	Coupling Coefficient	Tip Displacement, µm	Tip Rotation, rad	Voltage, V
12217	0.08	1.75	4.40E-5	27.0

Used Mason's 1D network model to determine movement of nodal plane



Fabrication and testing

Fabricated horn and tested its frequency response

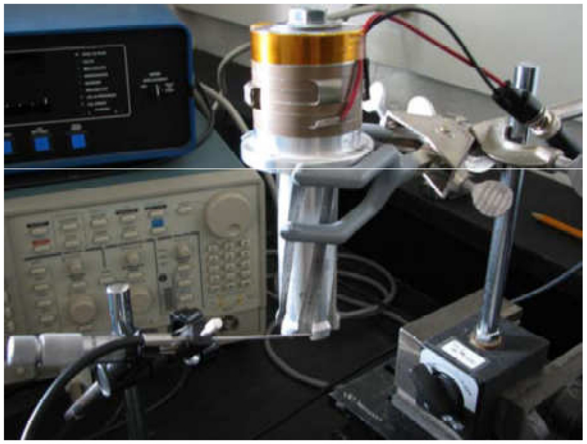


Transducer performance derived from impedance analysis.

First Resonant Frequency	Electromechanical Coupling Coefficient
11 972 Hz	0.07

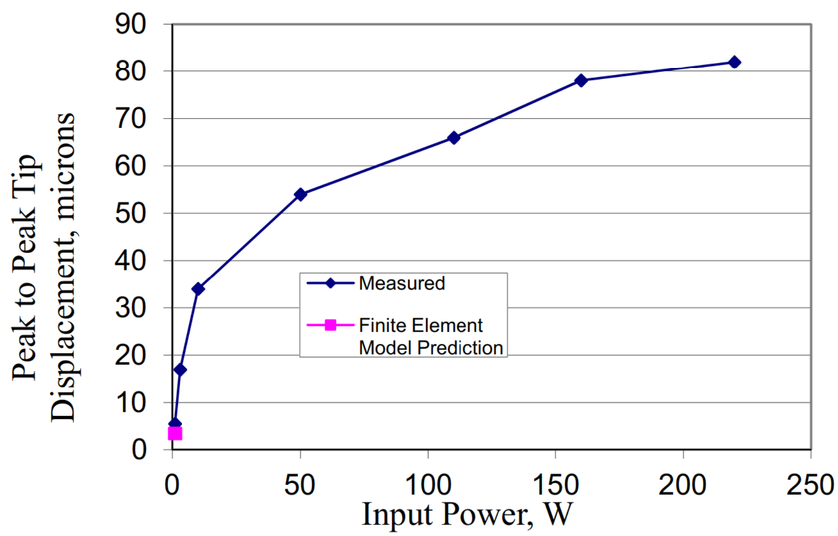
Fabrication and testing

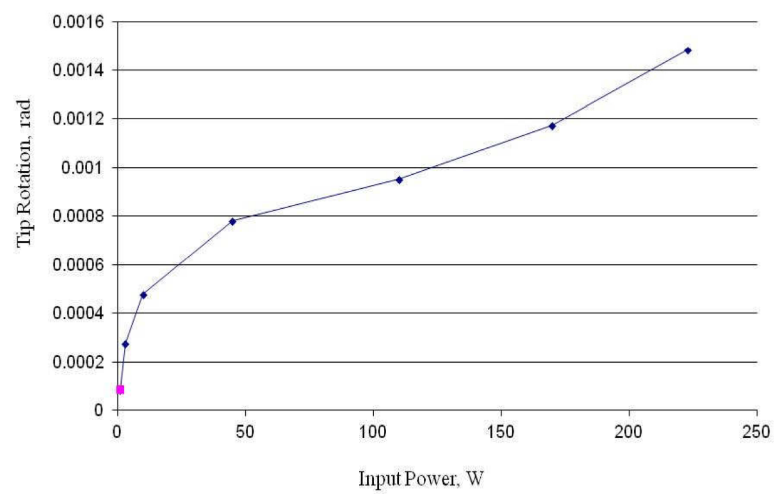
Testing of the horn tip displacement at resonance. A fotonics fiber optic sensor was used to test both the extension and rotation at the tip at the resonance frequency



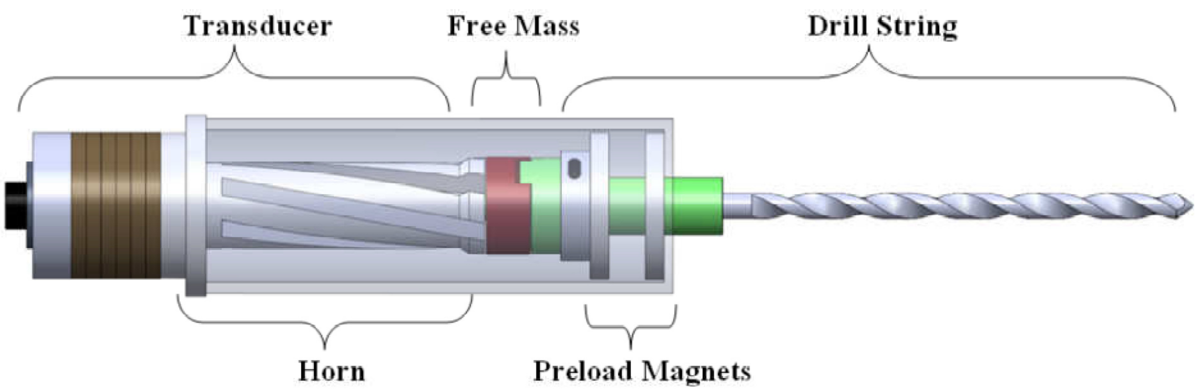
Testing

Comparison of FEM and experimental extension data small signal FEM predictions compare favorably to data at low power





Drill design and Fabrication

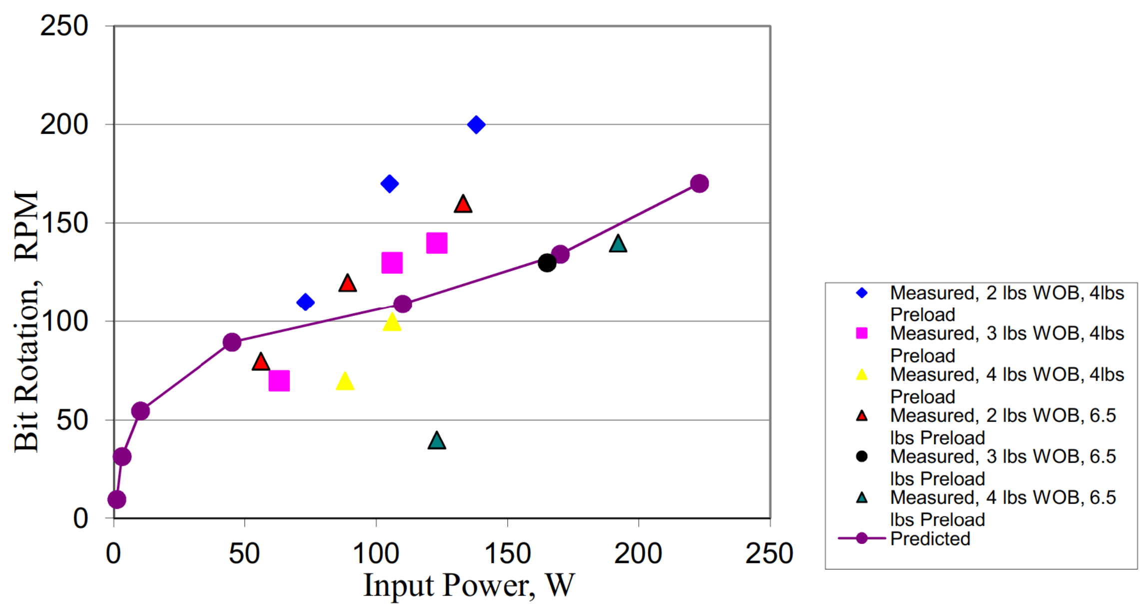


Impacts on free mass would transmit rotation to bit through key and still be free to expand in the axial direction. The bit and free mass preloaded using NeFeB magnets

Drilling action

Also noted at higher frequencies we could rotate in opposite direction

Drill Testing



Input Power, W	WOB, lbs	Preload, lbs	Duty Cycle	Drill Rate, mm/min
100	3	4	80 %	8

Testing

•A novel horn concept to produce hammering and rotation using a single piezoelectric transducer was investigated theoretically using a variety of modeling methods via MATLAB and ANSYS.

• A transducer design was fabricated and demonstrated simultaneous rotation and hammering.

•This Piezoelectric Rotary Hammer Drill prototype has not been optimized, and requires further development however the un-optimized version rotated at 200 RPM.

•We also noted that we could reverse the direction of rotation by driving at higher frequencies (2x)

•Future work should include considering different horn shape designs, in order to compare with the performance of this initial prototype.

•In addition looking at other geometries, horn materials such as Titanium may aid in increasing the electromechanical mechanical coupling.

Conclusions

- Ultrasonic Horns can be designed to produce many original mechanisms.

- We have just scratched the surface of Potential applications.

- We are still scratching

References

Bar-Cohen, Yoseph (2012) Mircea Badescu, Stewart Sherrit, Kris Zacny, Gale L Paulsen, Luther Beegle, Xiaoqi Bao, **“**Deep Drilling and Sampling via the Wireline Auto-Gopher Driven by Piezoelectric Percussive Actuator and EM Rotary Motor” Proceedings of the SPIE Smart Structures and Materials/NDE Symposium,vol 8345-78, San Diego, CA, March 12-15

Chang, Z. (2005), S. Sherrit, M. Badescu, X. Bao, and Y. Bar-Cohen, "Design and analysis of ultrasonic actuator in consideration of length reduction for a USDC (Ultrasonic/Sonic Driller/Corer)," Proceeding of the Industrial and Commercial Applications of Smart Structures Technologies, SPIE Smart Structures and Materials Symposium, Paper #5762-10, San Diego, CA, March 7 - 10, 2005.

Chang, Z. (2004), S. Sherrit, X. Bao, Y. Bar-Cohen “Design and analysis of ultrasonic horn for USDC (ultrasonic/sonic driller/corer)”, Proceedings of the SPIE Smart Structures Conference, SPIE Paper [5388-34], San Diego, CA., Mar 15-18.

Sherrit, Stewart(2002), Stephen A. Askins, Mike Gradziol, Benjamin P. Dolgin, Xiaoqi Bao, Zensheu Chang, and Yoseph Bar-Cohen, “Novel Horn Designs for Ultrasonic/Sonic Cleaning Welding, Soldering, Cutting and Drilling," Paper 4701-34, Proceedings of the SPIE Smart Structures and Materials Symposium, San Diego, CA, March 17-19

Sherrit, Stewart (1999), B.P. Dolgin, Y. Bar-Cohen, D. Pal, J. Kroh, T. Peterson "Modeling of Horns for Sonic/Ultrasonic Applications", Proceedings of the IEEE Ultrasonics Symposium, pp. 647- 651, Lake Tahoe, Oct 1999

Sherrit, Stewart (2008), Christopher M. Jones, Jack B. Aldrich, Chad Blodget, Xiaoqi Bao, Mircea Badescu, Yoseph Bar-Cohen, “Multilayer piezoelectric stack actuator characterization”, Proceedings of the SPIE 15th International Symposium on Smart Structures and Materials, San Diego, CA, SPIE Vol. 6929-8, 9-13 March

Sherrit, Stewart (2009), Kent Frankovich,Xiaoqi Bao, Curtis Tucker, “Miniature piezoelectric shaker mechanism for autonomous distribution of unconsolidated sample to instrument cells”, Proceedings of the SPIE 16th International Symposium on Smart Structures and Materials, San Diego, CA, Proc. SPIE 7290, 72900H

Sherrit, Stewart (2011), Xiaoqi Bao, Christopher M. Jones, Jack B. Aldrich, Chad J. Blodget, James D. Moore, John W. Carson, and Renaud Goullioud, “Piezoelectric Multilayer Actuator Life Test”, IEEE Trans. Ultrasonics, Ferroelectrics and Frequency Control. **58**, no. 4, pp. 820-828

Acknowledgements

This research was carried out at the Jet Propulsion Laboratory, California Institute of Technology, and was sponsored by National Aeronautics and Space Administration (NASA). Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise, does not constitute or imply its endorsement by the United States Government or the Jet Propulsion Laboratory, California Institute of Technology.

Advanced Technologies Group-
Xiaoqi Bao, Yoseph Bar-Cohen, Mircea Badescu, Jack Aldrich, Zensheu Chang, Ayo Olorunsola
Students: Luke Domm, Phillip Allen

MSL SAM
Jason Feldman
Steve Battel (Battel Eng.)

MSL CHEMIN
Allen Farrington
Bill Harris
Bob Debusk
Curtis Tucker
Dave Blake (Ames)
Dave Randall
Eric Olds (Swales)
Jennifer Dooley
John Koehler
Kent Frankovich
Phillippe Sarrazin (Inxitu)
Soren Madsen
Tim Mccann
Wayne Zimmerman

SIM
Ali Ghanneh
Bob Glaser
Brant Cook
Chad Blodgett
Dave Braun
Dave Van-Buren
Eric Reed
Jeff Sokol
John Carson
Mohamed Tehrani (Aerospace Inc.)
Paul MacNeal
Paul McGrath
Susan Trollier-McKinstry (Penn State)